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# An Evaluation of the Effectiveness of Ceiling Fans for Reducing Heating Requirements in Army Facilities

by
Lawrence J. Augustine

Many claims have been made for ceiling fans as energy saving devices. Fans destratify the air in a building; that is, they reduce the temperature differences between floor and ceiling. Depending on outside conditions, this can reduce heat loss. To quantify the effectiveness of fans during the heating season, USA-CERL, funded through a Facilities Engineering Applications Program (formerly FTAT) project, collected vertical thermal stratification measurements in Army buildings that had been equipped with ceiling fans. The buildings were located at Fort Carson, CO and Fort McClellan, AL. By analyzing how much the key building temperatures (ceiling, floor, and mean indoor) changed when ceiling fans were used, the USA-CERL engineers estimated the energy savings associated with fans.

The results showed that, in general, the buildings with the greatest initial stratification showed the greatest savings. In addition, the degree of thermal stratification was determined to be a linear function of outside air temperature. However, more research is needed to determine the relationship between stratification and building characteristics. Thus, the degree of stratification in a building and possible factors affecting it should be evaluated carefully before installing ceiling fans.





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Many claims have been made for ceiling fans as energy saving devices. Fans destratify the air in a building; that is, they reduce the temperature differences between floor and ceiling. Depending on outside conditions, this can reduce heat loss. To quantify the effectiveness of fans during the heating season, USA-CERL, funded through a FEAP project, collected vertical thermal stratification measurements in Army buildings that had been equipped with ceiling fans. The buildings were located at Fort Carson, CO and Fort McClellan, AL. By analyzing how much the key building temperatures (ceiling, floor, and mean indoor) changed when ceiling fans were used, the USA-CERL engineers estimated the energy savings associated with fans.

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The results showed that, in general, the buildings with the greatest initial stratification showed the greatest savings. In addition, the degree of thermal stratification was determined to be a linear function of outside air temperature. However, more research is needed to determine the relationship between stratification and building characteristics. Thus, the degree of stratification in a building and possible factors affecting it should be evaluated carefully before installing ceiling fans.

## FOREWORD

*This work was performed for the U.S. Army Engineering and Housing Support* Center (USAEHSC) under Project FTAT-ES-FG7, "Ceiling Fan Energy and Comfort Demonstration." Mr. B. Wasserman, CEHSC-FU, was the Technical Monitor.

The work was performed by the Energy Systems Division, U.S. Army Construction Engineering Research Laboratory (USA-CERL-ES). Dr. G. Williamson is Chief, USA-CERL-ES.

COL Carl O. Magnell is the Commander and Director of USA-CERL, and Dr. L. R. Shaffer is the Technical Director.

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# AN EVALUATION OF THE EFFECTIVENESS OF CEILING FANS FOR REDUCING HEATING REQUIREMENTS IN ARMY FACILITIES

## 1 INTRODUCTION

### Background

Ceiling fans have been promoted for several years as energy conservation devices. Substantial savings are claimed--as much as 30 percent by one manufacturer.[1] However, limited documentation exists on measured savings obtained by operating ceiling fans or other destatification devices. For Army installations to best use ceiling fans in meeting their energy goals, such claims need to be verified.

Fans destratify the air in a room or building by giving it velocity, thus creating a more uniform temperature distribution from floor to ceiling. Where thermal stratification has occurred in a room, air temperatures increase from floor to ceiling. The average air temperature in a stratified room with tall ceilings is higher than the temperature experienced by the room occupants. In the heating season, stratification results in a greater heat loss through the building envelope than when there is a uniform temperature distribution. In contrast, during the cooling season, stratification is beneficial: it reduces the heat gain through the ceiling and upper walls of a building. Since temperatures at the occupant level are lower than the average room temperature, a cooling system does not need to maintain a uniform temperature distribution to keep occupants comfortable.

Promoters of ceiling fans claim savings for both the heating and cooling seasons. Any savings realized during the heating season would arise from the differences in heating requirements between a stratified room and the same room with a uniform temperature distribution. Summer savings would result from the cooling effect that moving air has on human occupants: comfort could be maintained at a higher thermostat setting. However, limited documentation exists on measured savings obtained by operating ceiling fans or other destratification devices.

### Objective

The objectives of this investigation were to (1) demonstrate the energy saving potential of using ceiling fans to reduce heating requirements, (2) correlate outdoor temperature to the degree of stratification within structures, and (3) determine the best facilities for the application of ceiling fans.

### Approach

USA-CERL installed ceiling fans in a total of 10 buildings located at Fort Carson, CO and Fort McClellan, AL. The fans were installed according to the manufacturer's

[1] "Envirofans: The Climate Control System, manufacturer's literature, Envirofan Systems, Inc., Buffalo, NY, October 1984.

recommendations for the number and location of fans. Temperature stratification measurements were taken in these buildings. As-built drawings and engineering handbooks were used to estimate building heat transfer characteristics. Measured changes in the ceiling, floor, and mean temperatures as a result of ceiling fan operation were used to determine the magnitude of energy savings.

## Scope

The data and conclusions in this report apply only to the heating season. Entirely different processes occur in the cooling season.

## Mode of Technology Transfer

It is recommended that the results of this study be summarized in an Engineering Technical Note. An article on this work has been prepared for the Facility Technology Application Test (FTAT; now FEAP) Notebook.

# 2 ENERGY SAVINGS CALCULATIONS

Based on the assumptions that (1) stratification causes increased heat loss through the walls and ceiling and (2) the degree of stratification is a function of ceiling height, buildings with high ceilings will have the most stratification and the the most heat loss. Therefore, this effort focused on chapels, gymnasiums, warehouses, and theaters that have ceiling heights ranging from 15 ft to 40 ft.

No attempt was made to monitor energy consumption in the demonstration buildings, since the energy savings expected from the operation of ceiling fans was small when compared to a building's total energy use. Experience has shown that when monitoring building energy consumption, small energy savings are nearly impossible to extract from the normal variations that occur in consumption. Instead, energy heat loss equations and temperature measurements were used to calculate potential savings.

Industrial-grade fans were installed in 10 buildings: five at Fort Carson, CO (two gyms, a motor pool, a chapel, and a military clothing store) and five at Fort McClellan, AL (a chapel, a gym, a publications warehouse, and a commisary dry goods warehouse). The number of fans to be installed in a given building was found by dividing the total square footage by the coverage area of a single fan (provided by the manufacturer). The diameter of the fans depended on the ceiling height: 48 in. fans for ceilings less than 25 ft; 56 in. fans for ceilings over 25 ft.[2]

Air temperature gradients in a building were measured using an array of five Type-T (copper/constantan) thermocouples. One thermocouple was placed at the ceiling and one at the floor, and three were spaced evenly between the floor and ceiling. A sixth thermocouple measured the outdoor temperature. The thermocouples were scanned every 15 seconds using a Campbell Scientific CR10 Measurement and Control Module. Each scan contributed to a 15-minute running average. At the end of a 15-minute period the values were recorded and new running averages were started.

Temperatures were recorded over a 2-week period in early January 1988 at Fort McClellan and over 2 weeks in late January 1988 at Fort Carson. During 1 week at each site the fans were not used (stratified conditions); during the other week they were used (unstratified conditions). A wide variation of weather conditions was experienced at both installations during the two weeks of testing.

## Building Descriptions

Tables 1 and 2 list the important construction features of the demonstration buildings. They also show the number and and size of fans that were installed.

## Estimated Building Heat Loss Values

Using as-built drawings, the construction details and heat transfer characteristics of these buildings have been analyzed. Heat loss values (Btus/hr) were estimated using the areas (A) of the various components and thermal conductance (U) values found in the

[2] *The Intelligent Approach to Commercial/Industrial Ceiling Fans* (Leading Edge, 1985).

Table 1

Building Descriptions, Fort Carson

| Bldg. No. | Area sq ft | Roof | Walls | Ceiling Height | Heating System | Fans | General |
|---|---|---|---|---|---|---|---|
| **Motor Pool** | | | | | | | |
| 633 | 3840 | Flat, built-up | Concrete/concrete block; lots of windows; 7 overhead doors | 17 ft | 1 air handler, 4400 cubic feet per minute (CFM); 4 unit heaters, 2320 CFM each | 2 fans, 10,000 CFM each; 15 ft from end walls | ---- |
| **Gymnasiums (2)** | | | | | | | |
| 1856 & 2357 | 9156 | Built-up, on steel deck | 8-in concrete blocks, 1-in. mortar, 4-in. brick facing | 33 ft | 4 air handling units, on concrete pads supported by roof truss members | 4 fans, 21,000 CFM each | The two bldgs are mirror images |
| **Chapel** | | | | | | | |
| 1850 | 4692 | 4-in. redwood decking; roofing felt; exposed metal | Same as gyms | sloped: 13.5 min to 26.5 ft max | Constant volume system | 6 fans, 10,000 CFM each | Built same time as gyms |

**Table 2**

**Building Descriptions, Fort McClellan**

| Bldg. No. | Area sq ft | Roof | Walls | Ceiling Height | Heating System | Fans | General |
|---|---|---|---|---|---|---|---|
| **Chapel** | | | | | | | |
| 2293 | 4664 | 2-in. redwood planking; rigid insulation; built-up roof | 8-in., 3-core blks; 2-in. air space; 4-in., 3-core blks | Pitch: 2 rise, 12 run; min height 20.75 ft | Constant volume system; distribution at windows 4 ft above floor | 3 fans; 10,000 CFM each | ---- |
| **Commissary Dry Goods Warehouse** | | | | | | | |
| 2041 | 15852 | Steel deck; rigid insul.; vapor seal; built-up roof | 2 ext. walls: 8-in. blks w/insulated cores; 4 in. of grout; 4-in. brick face | 28 ft | 7 unit heaters | Six 48-in. fans, 10,000 CFM each | Largest bldg in test |
| **Theater** | | | | | | | |
| 2101 | 6324 | Steel deck; rigid insul.; built-up gravel roof | 10-in. blks.; 2-in. airspace; 4-in. brick facing | 17 ft to drop ceil. (7.5 ft between roof & ceiling) | Constant volume system; 6 diffusers at ceiling | 4 fans, 10,000 CFM each | |
| **Gymnasium** | | | | | | | |
| 1702 | 9626 | Steel deck; built up roof R19 insul. on drop ceiling | Concrete block; stucco exterior; | 28 ft (airspace above drop ceiling) | 2 large, high velocity air handlers | 4 fans, 21,000 CFM each | Very similar to Fort Carson gyms |

ASHRAE Handbook 1981 Fundamentals[3]. Values for infiltration and floor heat transmission were calculated using models presented in the *ASHRAE Fundamentals* (infiltration: Equation 18, p 22.13 and Equation 7, p 25.9; floor: Equation 6, p 25.8). The estimated heat loss values (UxA) are summarized in Table 3.

## Temperature Data

These estimated heat loss values are used with three key temperatures: ceiling, floor, and mean. A change in any of these temperatures affects the overall building heat transfer rate; a reduction will result in energy savings. These temperatures were measured to determine the extent of changes due to ceiling fan operation.

The data collected for each building over the 2-week period covered a wide range of outdoor conditions. At Fort McClellan the high for the period was 52 °F; the low was 22 °F (early January). At Fort Carson the 2-week high was 59 °F; the low was 10 °F. Preliminary data analysis indicated that the inside temperatures were affected by the outdoor temperature and direct comparison of an average of all stratified temperatures (fans off) and an average of all destratified temperatures (fans on) would be misleading because the degree of stratification depends on outside air temperature. It was necessary to organize the data into bins* based on outside temperature to get useful values for the changes in the key temperatures. Tables 4 and 5 (Fort Carson and Fort McClellan, respectively) list averages for ceiling, floor, ceiling-minus-floor, and mean temperatures in the stratified (s) and destratified (d) cases. The first column is the outdoor temperature bin. These tables show the effectiveness of ceiling fans for reducing stratification.

**Table 3**

**Heat Loss (UA) Parameters for Demonstration Buildings**

| | | Loss in Btu/hr/°F | | | | |
|---|---|---|---|---|---|---|
| **Building, #** | **Sq Ft** | **Wall** | **Window** | **Ceiling** | **Floor** | **Infilt.** |
| **Fort Carson** | | | | | | |
| Motor Pool, 633 | 3840 | 1636 | 1170 | 845 | 144 | 8400 |
| Gymnasium, 1850 | 9156 | 5400 | N/A | 1390 | 173 | 2880 |
| Gymnasium, 2357 | 9156 | 5400 | N/A | 1390 | 173 | 2880 |
| Chapel, 1850 | 4692 | 2100 | 1050 | 435 | 166 | 1010 |
| **Fort McClellan** | | | | | | |
| Chapel, 2293 | 4664 | 1110 | 1730 | 380 | 212 | 1170 |
| Warehouse, 2041 | 15862 | 1975 | N/A | 2460 | 182 | 4020 |
| Theater, 2101 | 6324 | 1790 | N/A | 950 | 258 | 1170 |
| Gymnasium, 1702 | 9626 | 1260 | N/A | 480 | 111 | 2985 |

[3]*ASHRAE Handbook 1981 Fundamentals* (American Society of Heating, Refrigeration, and Air-Conditioning Engineers, 1981).

*The bins here are 5-°F temperature ranges. Data in a bin corresponds to outside temperatures equal to or less than the bin value but greater than the next lowest bin value. For example, data for 35.0 °F, 32.5 °F, and 30.1 °F would fall in the 35 °F bin, but data for 30.0 °F would fall in the 30 °F bin. Data within a bin was averaged.

## Table 4

### Reduction in Key Temperatures (°F), Fort Carson

| Outdoor Temp | Ceiling (s)* | Ceiling (d)* | Floor (s) | Floor (d) | Ceil-Flr (s) | Ceil-Flr (d) | Mean (s) | Mean (d) |
|---|---|---|---|---|---|---|---|---|
| **Gym, 2357** | | | | | | | | |
| 35 | 78.69 | 71.49 | 67.39 | 65.42 | 11.30 | 6.06 | 73.37 | 68.33 |
| 30 | 78.92 | 72.10 | 66.63 | 65.64 | 12.30 | 6.47 | 73.01 | 68.86 |
| 25 | 82.03 | 69.01 | 67.58 | 63.90 | 14.45 | 5.10 | 75.19 | 66.34 |
| 20 | 73.71 | 66.36 | 64.89 | 62.00 | 8.82 | 4.36 | 69.45 | 64.11 |
| **Gym, 1856** | | | | | | | | |
| 35 | 73.17 | 81.85 | 64.60 | 74.45 | 8.56 | 7.41 | 68.94 | 78.17 |
| 30 | 75.28 | 81.32 | 65.63 | 73.67 | 9.64 | 7.65 | 70.81 | 77.49 |
| 25 | 76.87 | 81.38 | 65.17 | 72.65 | 11.71 | 8.72 | 71.43 | 77.36 |
| 20 | 76.50 | 81.49 | 63.77 | 68.25 | 12.73 | 13.24 | 70.35 | 76.76 |
| **Motor Pool, 633** | | | | | | | | |
| 45 | 75.24 | 72.51 | 64.54 | 60.17 | 10.69 | 12.36 | 69.01 | 65.63 |
| 40 | 76.33 | 73.75 | 64.57 | 58.84 | 11.76 | 14.92 | 69.50 | 65.29 |
| 35 | 80.24 | 73.52 | 61.05 | 57.78 | 19.20 | 15.74 | 69.71 | 65.22 |
| 30 | 79.40 | 74.41 | 62.09 | 58.59 | 17.31 | 15.83 | 70.12 | 66.14 |
| **Chapel, 1850** | | | | | | | | |
| 35 | 76.46 | 78.23 | 74.04 | 73.19 | 2.42 | 5.02 | 75.40 | 75.38 |
| 30 | 75.45 | 75.32 | 73.27 | 72.52 | 2.18 | 2.80 | 74.59 | 73.98 |
| 25 | 74.98 | 73.82 | 73.38 | 71.46 | 1.61 | 2.36 | 74.45 | 72.82 |
| 20 | 74.92 | 72.83 | 73.29 | 70.93 | 1.63 | 1.92 | 74.59 | 72.10 |

*Note: s = stratified (fans off); d = destratified (fans on).

Fort McClellan's gym is not included in Table 5 because of a failure in the data acquisition equipment. Temperature measurements are not available for when the ceiling fans were on. Data is available for the stratified case (fans off), however.

Tables 4 and 5 should be used with caution: values are averages obtained over a limited period of time. More extensive data collection would be necessary to reduce the anomalies that occur in the data. For example, Fort Carson gym (building 1856) had a runaway heating system during the first week of testing (destratified case, ceiling fans on). Thus, the high values for ceiling, floor, and mean temperatures were caused by the malfunctioning control system, not by the ceiling fans. In another case, heat loss at the Fort Carson motor pool (building 633) is caused primarily by infiltration and occupant behavior (e.g., opening and closing doors). In this building the highest degree of stratification existed when the floor temperature was about 50 °F; this low temperature can only be explained by opened overhead doors.

**Table 5**

**Reduction in Key Temperatures (°F), Fort McClellan**

| Outdoor Temp | Ceiling (s)* | Ceiling (d)* | Floor (s) | Floor (d) | Ceil-Flr (s) | Ceil-Flr (d) | Mean (s) | Mean (d) |
|---|---|---|---|---|---|---|---|---|
| **Theater, 2101** | | | | | | | | |
| 35 | 71.73 | 69.89 | 66.83 | 66.23 | 4.90 | 3.66 | 70.49 | 68.85 |
| 30 | 71.35 | 69.31 | 66.37 | 65.33 | 4.98 | 3.98 | 70.14 | 68.22 |
| 25 | 70.46 | 68.31 | 65.45 | 64.11 | 5.01 | 4.21 | 69.27 | 67.22 |
| **Commissary Warehouse, 2041** | | | | | | | | |
| 35 | 58.49 | 59.14 | 55.07 | 57.67 | 3.42 | 1.47 | 56.87 | 58.38 |
| 30 | 57.89 | 59.01 | 54.44 | 57.62 | 3.44 | 1.39 | 56.44 | 58.35 |
| 25 | 57.17 | 57.64 | 53.49 | 54.97 | 3.68 | 2.67 | 55.68 | 56.48 |
| **Chapel, 2293** | | | | | | | | |
| 35 | 62.62 | 68.00 | 61.46 | 66.00 | 1.17 | 1.99 | 62.37 | 67.54 |
| 30 | 64.53 | 68.56 | 62.54 | 66.34 | 1.99 | 2.21 | 64.08 | 68.04 |
| 25 | 65.05 | 63.12 | 62.58 | 61.89 | 2.47 | 1.24 | 64.51 | 62.89 |

*Note: s = stratified (fans off); d = destratified (fans on).

Also, one would expect to see a reduction in mean, ceiling, and ceiling-minus-floor temperatures and no change in the floor temperature. However, for the Fort McClellan warehouse and chapel, the ceiling, floor, and mean temperatures all increased with only a slight change in the ceiling-minus-floor temperature. These increased temperatures cause increased heat loss (these two buildings show negative savings; see Table 6). The interaction between the ceiling fans and the heating control system is unknown and may account for these anomalies.

Regardless of anomalies such as these, the tables show that ceiling fans affect stratification. In most of the demonstration buildings the fans reduced the ceiling-to-floor temperature difference. The other key temperatures were also lowered, with the ceiling temperature generally changing more than the floor temperature.

## Estimated Savings

The energy savings from using ceiling fans can be estimated by multiplying the appropriate heat loss parameters (Table 3) by the proper changes in key temperatures (calculated from Tables 4 and 5). The UA (heat transfer) value for the ceiling is multiplied by the change in ceiling temperature. The heat loss values for the walls, windows, and infiltration are summed and the total is multiplied by the change in mean temperature. The floor heat loss parameter is multiplied by the change in the floor

Table 6

Estimated Energy Savings From Ceiling Fan Operation

| Outside Temp | ΔT | | | Loss in Btu/hr | | | |
|---|---|---|---|---|---|---|---|
| | Ceiling | Floor | Wall&Infl | Ceiling | Floor | Wall&Infl | Savings |
| **Fort Carson Gym, 2357** | | | | | | | **Avg Savings = 60,766** |
| 35 | 7.20 | 1.97 | 5.04 | 10,008 | 341 | 41,731 | 52,080 |
| 30 | 6.82 | 0.99 | 4.15 | 9,480 | 171 | 34,362 | 44,013 |
| 25 | 13.03 | 3.68 | 8.85 | 18,112 | 637 | 73,278 | 92,026 |
| 20 | 7.36 | 2.89 | 5.34 | 10,230 | 500 | 44,215 | 54,946 |
| **Fort Carson Motor Pool, 633** | | | | | | | **Avg Savings = 49,137** |
| 45 | 2.73 | 4.38 | 3.37 | 2,307 | 631 | 37,764 | 40,702 |
| 40 | 2.57 | 5.73 | 4.21 | 2,172 | 825 | 47,177 | 50,174 |
| 35 | 6.72 | 3.27 | 4.48 | 5,678 | 471 | 50,203 | 56,352 |
| 30 | 4.99 | 3.51 | 3.98 | 4,217 | 505 | 44,600 | 49,322 |
| **Fort Carson Chapel, 1850** | | | | | | | **Avg Savings = 5,380** |
| 35 | -1.77 | 0.84 | 0.03 | (770) | 139 | 125 | (506) |
| 30 | 0.13 | 0.75 | 0.61 | 57 | 125 | 2,538 | 2,719 |
| 25 | 1.16 | 1.91 | 1.64 | 505 | 317 | 6,822 | 7,644 |
| 20 | 2.10 | 2.36 | 2.49 | 914 | 392 | 10,358 | 11,664 |
| **Fort McClellan Theater, 2101** | | | | | | | **Avg Savings = 16,937** |
| 35 | 1.84 | 0.61 | 1.64 | 4,526 | 111 | 10,373 | 15,010 |
| 30 | 2.03 | 1.03 | 1.92 | 4,994 | 187 | 12,144 | 17,325 |
| 25 | 2.14 | 1.34 | 2.05 | 5,264 | 244 | 12,966 | 18,475 |
| **Fort McClellan Commissary Warehouse, 2041** | | | | | | | **Avg Savings = (10,360)** |
| 35 | -0.65 | -2.6 | -1.51 | (1,599) | (473) | (9,551) | (11,623) |
| 30 | -1.12 | -3.17 | -1.9 | (2,755) | (577) | (12,018) | (15,350) |
| 25 | 0.47 | -1.47 | -0.79 | 1,156 | (268) | (4,997) | (4,108) |
| **Fort McClellan Chapel, 2293** | | | | | | | **Avg Savings = (11,527)** |
| 35 | -5.38 | -4.55 | -5.17 | (2,044) | (965) | (20,732) | (23,741) |
| 30 | -4.03 | -3.8 | -3.96 | (1,531) | (806) | (15,880) | (18,217) |
| 25 | 1.93 | 0.69 | 1.62 | 733 | 146 | 6,496 | 7,376 |

temperature. The sum of these products represents the total change in the heat loss of the building and the savings associated with the use of ceiling fans:

$$\text{Savings} = \Sigma(U_j A_j \cdot \Delta T_j) \qquad \text{Eq (1)}$$

where $U_j A_j$ is the overall heat transfer value in Btu/hr/°F for component, and $T_j$ is the change in temperature in °F for component j.

Table 6 presents the estimated savings for each of the demonstration buildings. The first column is the outdoor temperature at which the ceiling, floor, and mean temperatures were averaged. The next three columns are the changes in the key temperatures. These values were multiplied by the heat transfer parameters in Table 3 to get the Btus saved per hour at that outdoor temperature.

These results are very sensitive to the estimated heat transfer parameters, which are weighting factors that determine the importance of changes in the key temperatures. For example, at the Fort Carson motor pool, infiltration dominates the heat loss for the entire building. Thus, a small change in the mean building temperature (the temperature associated with infiltration) is more effective in saving energy than a more significant change in ceiling or floor temperatures. Also, differences between the estimated heat transfer parameters and the true value can cause a substantial error in the amount of energy actually saved. Because it was impossible to control all variables affecting building heat transfer (especially occupant behavior), the results presented in Table 6 need to be viewed with caution.

Two of the six buildings represented in Table 6 have negative savings associated with the operation of ceiling fans. These buildings did not show any severe stratification conditions during the period when temperatures were measured. No energy savings were computed for Building 1856 at Fort Carson because of the previously discussed problem with the building heating system during the first week of the test.

Table 6 shows that the savings associated with ceiling fan operation increase as the outside temperature decreases. Thus, heating energy savings associated with outdoor temperatures greater than 35 °F can be assumed to be small, since savings below that temperature are already small compared to total consumption. Since the changes in the key temperatures are not known for temperatures greater than 35 °F, annual savings figures must be based on the known quantities. For Fort Carson, there are 1940 hours in an average year that the outside temperature is between 35 and 20 °F (the range for data in this test). There are an additional 299 hours when the outside temperature is colder than 20 °F, making a total of 2239 hours below 35 °F. Similarly, Fort McClellan experiences an annual average of 511 hours of outdoor temperatures between 35 and 25 °F (the measured range) and 33 hours when the temperature is below 25 °F; the total at Fort McClellan is 544 hours.[4] The total number of hours below 35 °F is multiplied by the hourly savings (Btus/hr) to obtain an estimate of the average annual energy savings (Btus). Table 7 presents the results for buildings that showed positive energy savings.

[4] *Engineering Weather Data*, Army Technical Manual 5-785, NAVFAC P-89, Air Force Manual 88-29 (Departments of the Army, Air Force, and Navy, 1 July 1978).

Table 7

Annual Dollar Savings From Ceiling Fan Operation

| | Hourly Savings Btu/Hr | Annual Savings MBtu | Costs | Net Savings |
|---|---|---|---|---|
| Fort McClellan Theater, 2101 | 16,937 | 9.21 | $ 7.20 | $ 48.06 |
| Fort Carson Gym, 2357 | 60,766 | 136.05 | 29.52 | 786.78 |
| Fort Carson Motor Pool, 633 | 49,137 | 110.01 | 14.76 | 645.30 |
| Fort Carson Chapel, 1850 | 5,380 | 12.04 | 5.40 | 66.84 |

Table 7 also shows operating costs and net savings. The ceiling fans installed at Fort Carson and Fort McClellan use approximately 55 W of electrical energy when operating at normal speed. The annual operating costs were computed using Equation 2:

$$\text{Cost (\$)} = 55\ \text{W} \times \text{hours below } 35\ ^\circ\text{F} \times \frac{\$0.06}{\text{kWh}} \times \frac{1\text{kW}}{1000\text{W}} \times \#\text{ of fans} \qquad \text{[Eq 2]}$$

The net savings in Table 7 were calculated by multiplying the annual savings in MBtus by $6.00/MBtu for natural gas, then subtracting the annual operating costs.

USA-CERL contracted for the installation of ceiling fans for Fort Carson and Fort McClellan. Forty-eight fans were installed at a total contract price of $15,472, which included all material and labor. The average cost per installed fan was $322.00. Thus for the best case, Fort Carson Motor Pool, the estimated savings show a simple payback of just under 2 years. (The Fort Carson gym, 2357, appears to have greater savings, but it has four fans.)

The amount of savings depends strongly on the degree of stratification, since the two buildings with the greatest stratification (Fort Carson gym, 2357, and motor pool) had the greatest savings. For the demonstration buildings, stratification was not a severe problem. The ceiling to floor temperature difference exceeded 10 °F only for the two buildings just mentioned. For the other buildings the difference was generally less than 5 °F. Tables 6 and 7 show that if severe stratification does not exist, savings will be small or nonexistent.

# 3 STRATIFICATION AND OUTDOOR AIR TEMPERATURE

The amount of energy that can be saved using ceiling fans is directly related to the magnitude of thermal stratification in the building. Thus, identifying parameters that influence stratification is critical in determining where ceiling fans can be most effective. No previous work is available that provides a model for predicting the amount of stratification as a function of outdoor air temperature and building characteristics. The temperature stratification measurements taken during the demonstration project were analyzed to determine a method for predicting stratification within buildings.

Data were used only from the three buildings that indicated a stratification condition (ceiling to floor temperature difference greater than 10 °F). These three were Fort Carson buildings 1856, 2357, and 633 (the two gyms and the motor pool). Regression analyses were performed on the entire data set for each building to establish the relationship between outdoor air temperature, building conditions, and thermal stratification.

In addition, stratification data was collected at the USA-CERL highbay for 18 consecutive days in December 1987. This 6750-sq ft warehouse is constructed of 8-in. concrete blocks, with a 2-in. airspace between these and a 4-in. brick facing. Above the 40-ft ceiling, the roof consists of a steel deck, insulation, and built-up gravel. This space is heated by a constant volume system, with a diffuser at the ceiling.

Temperature data were taken in the highbay with the same equipment and methods used in the demonstration buildings. All data were taken in stratified conditions. The outdoor air temperature ($T_{out}$), ceiling-minus-floor temperature ($T_{cf}$), and the mean indoor temperature ($T_{in}$) were averaged into 15-minute values. The difference between the mean indoor temperature and the outside air temperature ($T_{in} - T_{out}$) was computed for each 15-minute interval. Each interval constituted a data set.

A total of 1430 data sets from the highbay were organized into 2.5 degree temperature bins based on the difference $T_{in} - T_{out}$. Within each bin all $T_{cf}$ and $T_{in} - T_{out}$ values were averaged. For example, if the temperature bin is 35 °F, the values would be averaged for all data sets where 32.5 °F < ($T_{in} - T_{out}$) <= 35 °F. The end result is a data table that contains the averaged $T_{cf}$ differences and the averaged $T_{in} - T_{out}$ differences for a series of 2.5 degree temperature ranges. Table 8 shows the temperature bin data for the USA-CERL highbay.

Linear regression analysis was done using $T_{in} - T_{out}$ (column 2, Table 8) as the independent variable and $T_{cf}$ (column 3, Table 8) as the dependent variable. Simple linear regression showed that a relationship exists, but $T_{in} - T_{out}$ accounts for only about 69 percent of the variation in the ceiling to floor temperatures. A graph of the bin data indicates that a curvilinear model would provide better regression results.

To use such a model, the $T_{in} - T_{out}$ values were squared for each temperature bin. In the regression, $T_{in} - T_{out}$ and $(T_{in} - T_{out})^2$ were the independent variables ($x$ and $x^2$). $T_{cf}$ again was the dependent variable. The regression results indicate a high correlation. Effectively, 92 percent of the variation in $T_{cf}$ can be explained by the difference between the mean indoor and outside air temperatures. Figure 1 shows the relationship between $T_{in} - T_{out}$ and $T_{cf}$.

## Table 8

**USA-CERL Highbay Temperature Data**

| Range | Mean Indoor - Outside Air ($T_{in}$ - $T_{out}$) | Ceiling - Floor ($T_{cf}$) | # of Sets in Bin |
|---|---|---|---|
| 60.00 | 58.82 | 11.89 | 15 |
| 57.50 | 56.27 | 11.57 | 8 |
| 55.00 | 53.60 | 10.38 | 27 |
| 52.50 | 51.17 | 6.20 | 74 |
| 50.00 | 48.78 | 5.61 | 39 |
| 47.50 | 46.16 | 5.25 | 49 |
| 45.00 | 43.56 | 3.93 | 60 |
| 42.50 | 40.98 | 3.02 | 72 |
| 40.00 | 38.77 | 3.04 | 116 |
| 37.50 | 36.25 | 2.53 | 113 |
| 35.00 | 33.79 | 2.72 | 138 |
| 32.50 | 31.13 | 2.46 | 128 |
| 30.00 | 28.90 | 3.07 | 129 |
| 27.50 | 26.35 | 3.12 | 92 |
| 25.00 | 23.79 | 2.42 | 70 |
| 22.50 | 21.27 | 2.48 | 99 |
| 20.00 | 18.63 | 2.41 | 65 |
| 17.50 | 16.34 | 1.86 | 71 |
| 15.00 | 14.05 | 1.92 | 58 |

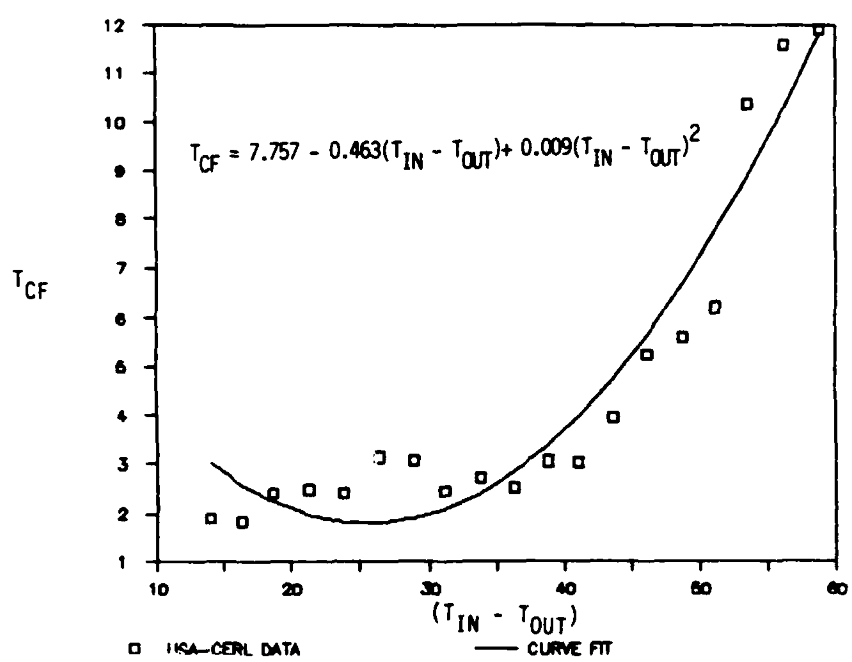


**Figure 1. Result of regression analysis, USA-CERL highbay.**

The same type of analysis was performed for the Fort Carson gyms and the motor pool. Unfortunately, the results did not parallel the findings from the USA-CERL high-bay: these results showed that the relationship between $T_{cf}$ and $T_{in} - T_{out}$ is strongly linear. For Buildings 633, 2357, and 1856 (respectively), 89 percent, 86 percent, and 65 percent of the variation in ceiling to floor temperature differences can be explained by the $T_{in} - T_{out}$ values. Figures 2 through 4 show the results for the Fort Carson buildings.

The results indicate that the relationship between the degree of stratification and outside temperature can be readily defined for a specific building, given temperature data, but at this time it cannot be predicted in a general formula. Building characteristics such as infiltration and solar gains have an undetermined quantitative effect on this relationship. Additional work needs to be conducted on relating the degree of stratification to building characteristics, developing a more complex model, and gathering more extensive data to validate the model.

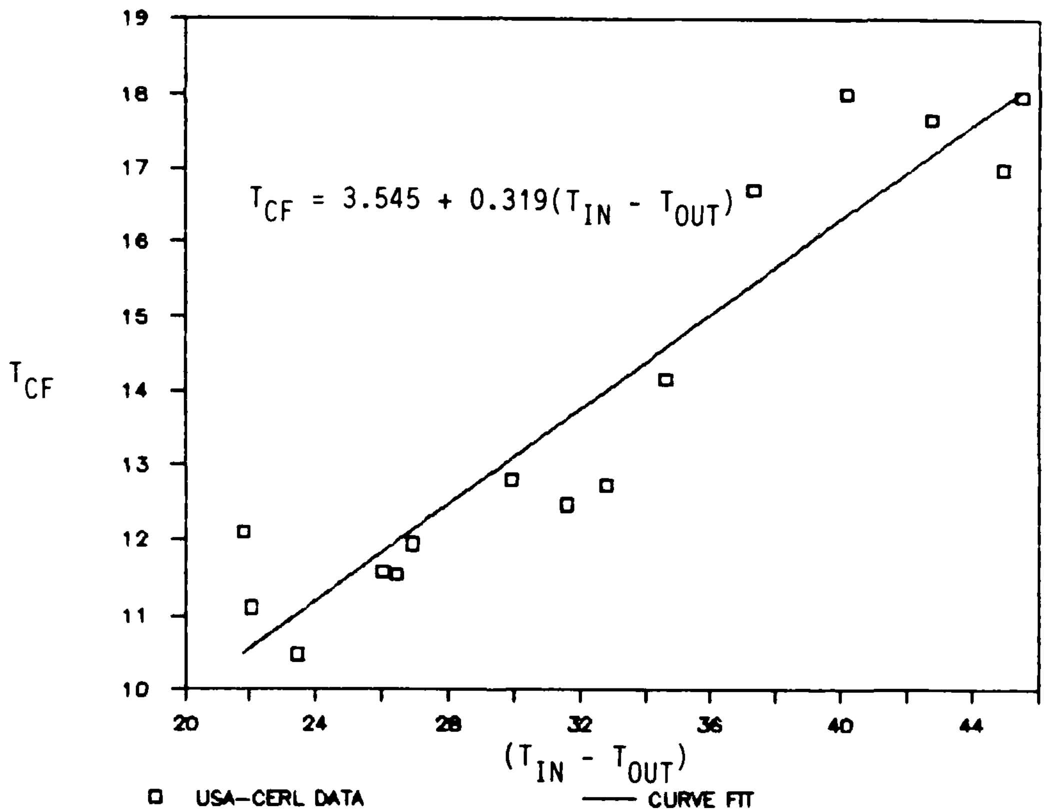


**Figure 2. Result of regression analysis, Fort Carson motor pool, building 633.**

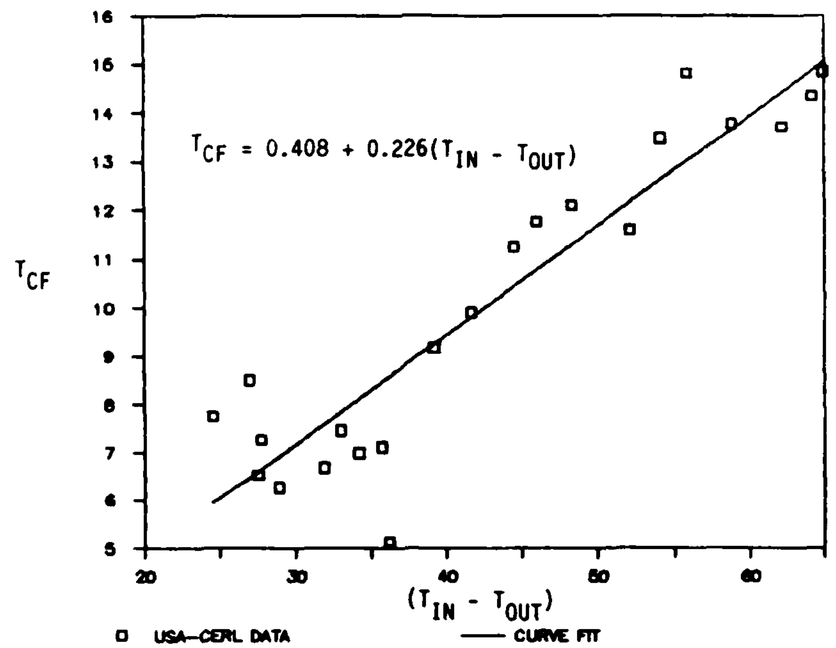


**Figure 3. Results of regression analysis, Fort Carson gym, building 2357.**

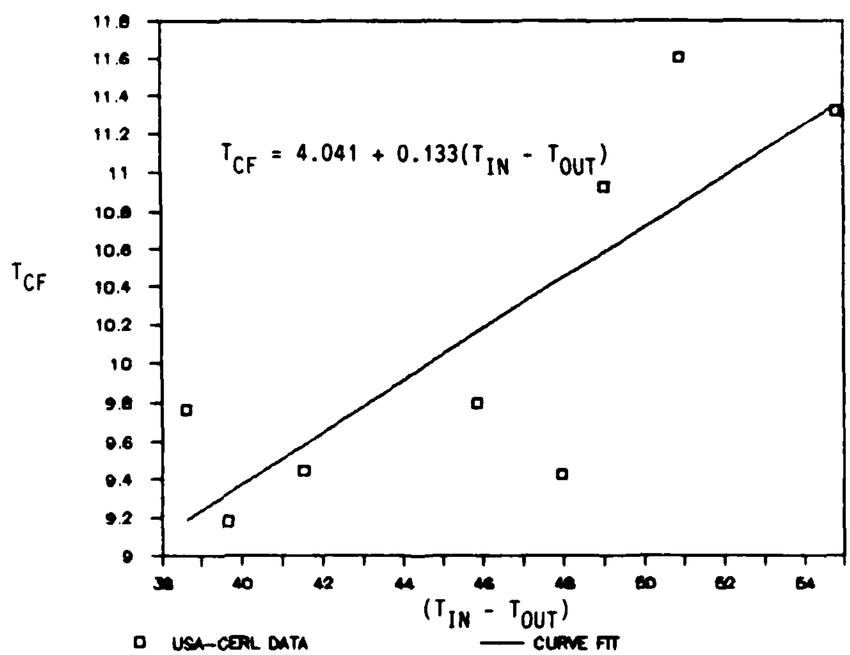


**Figure 4. Results of regression analysis, Fort Carson gym, building 1856.**

# 4 CONCLUSIONS AND RECOMMENDATIONS

Data collected at 10 Army buildings indicate that ceiling fans could possibly be used to save energy during the heating season. Because the initial cost of a ceiling fan is low, they may be cost effective even though the estimated savings for the demonstration buildings are small. Ceiling fans may become more economical when the degree of thermal stratification within a building increases. The demonstration buildings had relatively low amounts of thermal stratification.

As seen in Table 2, ceiling fans affect the stratification in buildings. The operation of ceiling fans during the heating season reduces the ceiling to floor temperature difference and in most cases reduces the mean temperature. However, these reductions do not always result in energy savings. Several of the buildings where data was collected showed an increase in the estimated hourly energy losses (Table 6). These buildings generally did not have a stratification problem. It is critical that the degree of stratification be evaluated before installing ceiling fans. If stratification is not a problem, then ceiling fans will not be effective in saving energy.

Thermal stratification in buildings is a complex process that depends strongly on the difference between the mean indoor temperature and the outdoor temperature. Thermal stratification is also affected by building characteristics, but the quantitative relationship is not known. More research is needed to define this relationship in a more complex model before general statements can be made about the effectiveness of ceiling fans in Army buildings.

However, certain qualitative conclusions about the characteristics which influence stratification can be formulated from the demonstration. In general, buildings that have forced air heating systems with supply ducts or unit heaters near the ceiling will have greater stratification than buildings with distribution systems near the floor. The buildings with the greatest amount of stratification (USA-CERL highbay, Fort Carson gyms and motor pool; see Tables 4, 5, and 8) have heating systems in which hot air enters the room near the ceiling. The chapels at Fort Carson and Fort McClellan have distribution system from around the floor level; these buildings do not show stratification problems.

Heating systems with low air supply velocity will increase stratification. The gymnasiums at Fort Carson have relatively low velocity air handlers, which are also located near the ceiling, and both buildings show stratification. In contrast, the gymnasium at Fort McClellan is very similar in construction to the Fort Carson gyms but has two air handlers with higher discharge rates; practically no stratification occurs there.

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